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WIGWAM WASTE BURNER GUIDE AND DATA BOOK. A MANUAL FOR THE IMPROVED COMBUSTION OF WOOD WASTE IN WIGWAM WASTE BURNERS

Oregon State Sanitary Authority
Portland, Oregon

March 1968

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A MANUAL FOR THE IMPROVED COMBUSTION OF WOOD WASTE IN WIGWAM WASTE BURNERS

This project is supported in part by Public Health Service Project Grant No. 68C 40051 made by the Division of Air Pollution under P.L. 88-206, the Clean Air Act.

OREGON STATE SANITARY AUTHORITY
A DIVISION OF THE OREGON STATE BOARD OF HEALTH
STATE OFFICE BUILDING
1400 S. W. 5TH AVENUE
PORTLAND, OREGON 97201

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Subdivision 4

CONSTRUCTION AND OPERATION OF WIGWAM WASTE BURNERS

[ED. NOTE: Unless otherwise specified, sections 24-005 through 24-025 of this Chapter of the Oregon Administrative Rules Compilation were adopted by the State Sanitary Authority, June 24, 1965 and filed with the Secretary of State, July 6, 1965 as Administrative Order SA 22.]

24-005 DEFINITIONS. (1) "Approved" means approved in writing by the Sanitary Authority staff.

(2) "Wigwam Waste Burner" means a burner which consists of a single combustion chamber, has the general features of a truncated cone, and is used for incineration of wastes.

(3) "Continuous-flow conveying methods" means methods which transport materials at uniform rates of flow, or at the rates generated by the production process.

Hist: Filed 10-16-67 as SA 28

24-010 WIGWAM WASTE BURNERS-PURPOSE. Section 24-010 through Section 24-020 are adopted for the purpose of controlling, preventing, or reducing air pollution or public nuisance caused by smoke, gases and particulate matter discharged into the air from wigwam waste burners.

Hist: Filed 10-16-67 as SA 28

24-015 WIGWAM WASTE BURNER CONSTRUCTION PROHIBITED. Construction of wigwam waste burners is hereby prohibited after July 1, 1965, unless plans and specifications have been submitted to and approved by the Sanitary Authority prior to construction.

24-020 WIGWAM WASTE BURNER USE RESTRICTED. No person shall use a wigwam waste burner for the incineration of other than production process wood wastes. Such wood wastes shall be transported to the burner by continuous-flow conveying methods.

Hist: Filed 10-16-67 as SA 28

24-025 Repealed 10-16-67 by SA 28

ANALYSIS OF DATA FROM 1967 SURVEY OF
SAWMILL WASTE BURNERS

by

Oregon State University
(100 tests on 19 burners)

Emission Temperature: Low 90°F. High 1500°F
Particulate Emissions: Low 0.004 grain/ft^3, High 0.607 grain/ft^3
Low 0.17 lb/ton fuel, High 26.94 lb/ton fuel

Correlations:

1. Particulate emission correlates inversely with emission temperature. The higher the temperature, the lower the emission.

2. Draft ratio (actual/theoretical) correlates directly with temperature. Higher temperature is achieved with a tighter burner (better maintenance and door closed!)

3. Percent of ash in the emission correlates directly with temperature. Higher emission temperature indicates more complete combustion.

Important Non-Correlations:

1 The size of the particulate was not correlated with temperature.

2. The temperature was not correlated with fuel rate only.

3. The emission (per cubic foot of gas) was not a function of the fuel consumption rate.

An Analysis of Variance Indicated:

1. That the temperature of different burners was significantly different.

2. That the emission (grains per ft^3) from different burners was significantly different.

3. That the size distribution of the particulate from different burners was significantly different.

PREFACE

This manual has been prepared by H. W. McKenzie of the Air Quality Control staff of the Oregon State Sanitary Authority as an aid in the reduction of emissions from the State's existing wigwam waste burners.

Section I of the manual presents the combustion concepts which apply, and Section II provides handbook data for use in engineering design.

The author wishes to express appreciation to Dr. R. W. Boubel of Oregon State University for his review and comment, and for the basic information provided in O.S.U. Engineering Experiment Station Circular Number 34 to which the reader is referred.

This project is supported in part by Public Health Service Project Grant No. 68C 40051 made by the Division of Air Pollution under P.L. 88-206, the Clean Air Act.

H. M. PATTERSON, Chief
Air Quality Control Section

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1. COMBUSTION CONCEPTS . WASTE MEASUREMENT

COMBUSTION REQUIRES OXYGEN

Simply stated, combustion is the chemical reaction in which oxygen combines with a fuel at a rate sufficient to produce heat and visible light.

Some fuels combine with oxygen quite readily. Others combine more slowly, and some need outside help to combine at all. The outside help usually consists of providing additional heat to raise the temperature.

Most rocket boosters used to launch vehicles into space are fueled by a refined kerosene and oxygen. These combine very readily the instant they are brought together in the nozzle. They may not even need outside help to ignite. In combining, they quickly release tremendous quantities of energy, heat and light. Very rapid rates of combustion are classed as explosions.

As an opposite extreme, steel or iron combine with oxygen very slowly to form rust. This is classed as an oxidation process. Heat is given off, but at such a slow rate that we are not aware of it.

Somewhere between these extremes, material can combine with oxygen at a rate which produces observable heat, but not observable light.

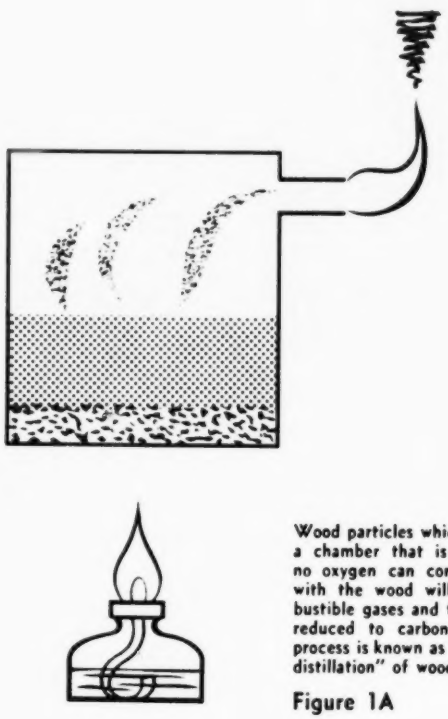
Wood chips in a storage pile combine very slowly with the oxygen present in the air between and in the chips to produce heat within the pile. Because wood is a good insulator the heat is confined, and accumulates, resulting in a temperature buildup. As the temperature rises, the reaction is enhanced and can get out of hand if sufficient oxygen is present.

By this we mean that the oxidation rate can produce sufficient heat to reduce the wood to carbon, and then even to ignite the carbon. Upon ignition, the oxidation rate increases quite suddenly, and the accompanying increase in heat triggers the ignition of additional material. A generous supply of oxygen becomes available if the process reaches the outside atmosphere. When this happens, it's time to call the fire department.

The rate at which oxygen combines with a fuel thus determines whether the reaction is accompanied by higher temperatures and visible light.

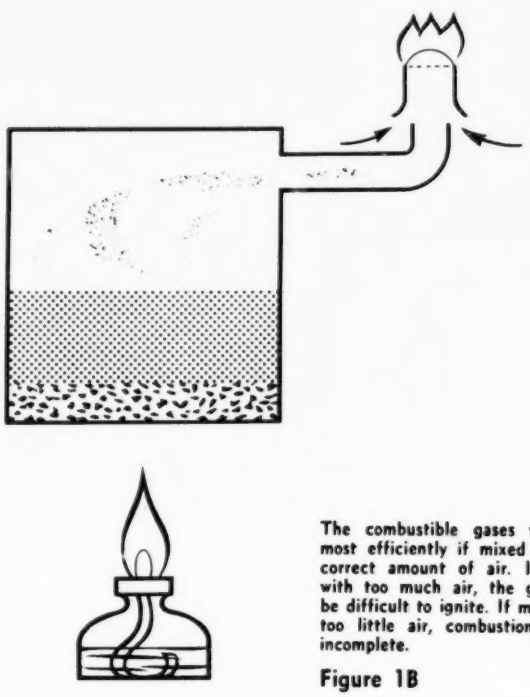
WOOD DECOMPOSES WHEN HEATED

We spoke of wood chips being reduced to carbon. This takes place through a process that old mother nature has used for centuries in making coal and natural gas. The process is known as destructive distillation, or "pyrolytic decomposition."



Wood particles which are heated in a chamber that is closed so that no oxygen can come into contact with the wood will give off combustible gases and the wood will be reduced to carbon and ash. The process is known as the "destructive distillation" of wood.

Figure 1A



The combustible gases will burn most efficiently if mixed with the correct amount of air. If diluted with too much air, the gases will be difficult to ignite. If mixed with too little air, combustion will be incomplete.

Figure 1B

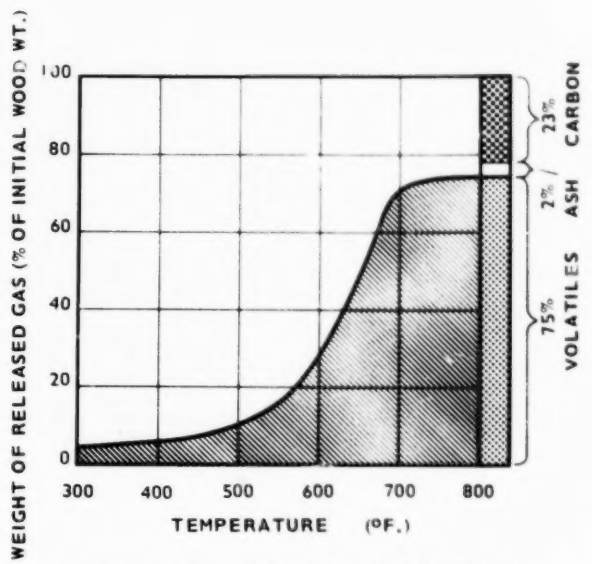
This process can be illustrated with a simple demonstration. First, we place some wood particles in a chamber that can be completely closed except for a small opening near the top. Then we apply heat to the bottom of the chamber.

As the temperature is increased, the wood particles will give off a series of gases that will soon appear as smoke issuing from the outlet opening. After a short period, the gases being generated will have purged all the air from the chamber and there will thus be no oxygen in contact with the wood. With no oxygen present, combustion cannot take place, only distillation of the volatile portions of the wood.

First the moisture will be evaporated from the wood and will escape from the outlet in the form of water vapor or steam. Following this, a number of chemical compounds will be emitted in the form of volatile gases, all of which mixed together are combustible and are referred to as "producer gas." When the volatiles are all driven off, nothing will remain but carbon and ash. We will have separated the wood into the following components by approximate weight:

Carbon	23%
Volatile matter	75%
Ash	2%

The ash will be mixed with the carbon remaining in the bottom of the chamber, but the volatiles will have escaped.



DESTRUCTIVE DISTILLATION OF WOOD

Douglas fir, which is heated progressively to 800 degrees F. will give off volatile matter in the form of combustible gas at the rate of 6.5 cu. ft. of gas per pound of drywood. The gas has a heating value of approximately 420 Btu per cubic foot.

Figure 1C

Both the carbon and the volatiles will burn in the presence of oxygen.

THE PRODUCED GAS IS A GOOD FUEL

The volatiles that we distill from the wood in reducing it to carbon are a combustible gas. In fact, they're a pretty good fuel, having almost half the heat content of natural gas.

Just as with natural gas, our "producer gas" requires oxygen to burn. We can burn the gas stream in the open air without prior mixing with air, but it will take longer for combustion to be complete. This is because the gas stream in in contact with air only at its outer surface, and tends to create a carbon dioxide shield around itself as it burns. To reach the unburned gas, air must penetrate this shield. For this reason, combustion will be more efficient if we provide **turbulence** to mix air with the gas stream, so that oxygen can be brought into contact with all portions of the producer gas.

The producer gas contains quite a bit of moisture, which is incombustible, and air is about 75% nitrogen, which is also incombustible, so the air-gas mixture must be in about the correct proportion for best combustion. If we don't provide enough air to supply all the oxygen needed, we'll only obtain partial combustion, and if we dilute the producer gas with too much air, the mixture will be difficult to ignite.

The producer gas, in association with oxygen, has an **ignition temperature** of about 1000° F. If it cools below this temperature, it will cease to burn and appear as grey smoke. We must thus help things along by assuring that the ignition temperature is maintained for a sufficient period of **time** for oxygen to combine with all of the combustible gas.

Under certain conditions, the combustible gas decomposes, releasing carbon in the form of minute particles. These must also combine with oxygen to burn completely. Their ignition temperature is about 640 degrees, and if their **temperature** falls below this point, they will cease to burn and appear as black smoke.

The conditions necessary for complete gas combustion which we have discussed to this point can be summarized with three words:

1. **Time,** for oxygen to combine with all of the combustible gas and suspended carbon.
2. **Temperature,** to maintain ignition, and
3. **Turbulence,** to assure mixing so that oxygen will reach all of the combustible gas and carbon in spite of the carbon dioxide and nitrogen that get in the way.

BURNING CARBON PROVIDES THE HEAT

In the foregoing example, we heated wood particles in a closed chamber until all of the volatiles were driven off and only carbon and ash remained. We can remove the carbon from the chamber and burn it just as you do with your backyard barbecue briquets, in which case the carbon will combine with the oxygen in the air to form carbon dioxide or carbon monoxide.

The thin blue flames you sometimes see chasing around over the hot coals in your barbeque are carbon monoxide burning to carbon dioxide. The carbon monoxide was formed when some of the carbon couldn't find enough oxygen to burn to carbon dioxide, so it combined with half as much forming carbon monoxide, and the carbon monoxide then found the rest. So carbon monoxide is a combustible gas, too. As a fuel it has about one-third the heat content of natural gas.

Let us suppose, then, that we make a little oxygen available to the carbon in the bottom of the chamber so that it can burn. The combustion of the carbon will then provide the heat required to distill the volatiles from the wood and the outside heat source can be removed. We will then have a self-sustaining process that manufactures its own carbon fuel with the heat from carbon combustion. It will also manufacture producer gas which we can mix with air and burn quite efficiently. All that we need to supply are fuel and oxygen at the rate they are consumed.

What we have described is actually an over simplification to explain the principle of a gas producer, a device which may be centuries old. It is a matter of record that a man named M. Philip Lebon made use of gas from wood in 1799, and succeeded in lighting his house with it in 1801.

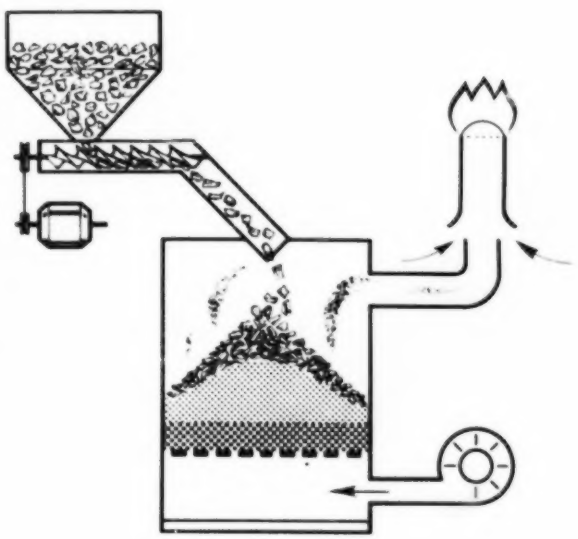
DUTCH OVEN BOILERS ARE SIMILAR

The combustion of wood waste in a dutch oven boiler utilizes much the same basic process that we have described. The principal difference is that in a dutch oven boiler we mix air with the producer gas as it leaves the fuel bed, and burn it within the chamber. The hot flue gases leaving the combustion chamber are those resulting from the combustion of both the carbon and the producer gas.

Air is supplied to the carbon through grates beneath the fuel pile, and is supplied to the producer gas through openings above the fuel pile. For efficient combustion, the underfire and overfire air quantities must be carefully adjusted. In practice, it is found that in a dutch oven boiler about 20% more overfire air must be provided than theoretically required to assure that oxygen will reach all portions of the combustible gas.

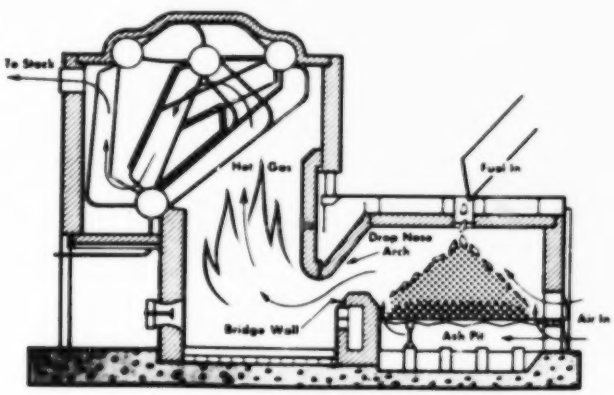
WIGWAM BURNERS CAN BE ADAPTED

Just as in the dutch oven boiler, the basic principles of destructive distillation can be utilized to attain efficient combustion in a wigwam waste burner.



If we supply the correct amount of oxygen to the carbon so that it will burn, the heat generated will sustain the destructive distillation process and the outside heat source can be removed. The process will be continuous if we supply new fuel at the rate it is consumed.

Figure 1D



DUTCH OVEN BOILER

A conventional dutch oven boiler utilizes the principles of destructive distillation. Combustible gas emerging from the fuel pile mixes with air entering through the overfire air ports and the fuel charging chute. The air-gas mixture burns in the combustion chamber.

Figure 1E

Let's take a new look at the gas producer that we discussed previously. If we substitute for the cylindrically shaped refractory gas producer a conically shaped metal enclosure, the similarity to a wigwam burner is readily apparent. The obvious differences are that a wigwam burner has an open top, and the gases are mixed with air and burned inside the enclosure.

This arrangement has both advantages and disadvantages. One advantage is that heat from the burning gases assists in drying the incoming fuel. The principal disadvantages result from the enclosure being constructed of metal rather than refractory. Bare metal dissipates heat quite rapidly, so that gas ignition temperatures are more difficult to maintain. At the same time, a steel structure will buckle and eventually fail if subjected to very high temperatures. However, with proper attention to details of design, construction and operation, the wigwam burner can be made to perform with amazing combustion efficiency.

The approach to efficient combustion in a wigwam burner must be through the avenue of destructive distillation, with combustion of the carbon and of the producer gas considered as separate, but interrelated functions.

SUCCESS DEPENDS ON CORRECT DESIGN

There are eight basic requirements for efficient combustion in a wigwam waste burner. Deficiency in any of the eight can mean the difference between a successful and an unsuccessful installation. As a guide in upgrading an existing burner installation, the following will serve as a check list. Each will be discussed in detail in subsequent chapters.

1. **ADEQUATE FUEL QUANTITY.** Fuel must be consistently delivered to the burner at an adequate rate for the burner size. Stated another way, the burner must not be too large for the rate of fuel delivery.
2. **ADEQUATE FUEL CHARACTERISTICS.** Physical characteristics of the fuel must be compatible with the destructive distillation concept. Materials that are predominantly either very fine or very coarse may require specialized treatment or methods.
3. **A CORRECTLY DESIGNED UNDERFIRE AIR SYSTEM.** The system must be adjustable and must distribute air uniformly and at the correct rate to all portions of the base of the fuel pile.
4. **A CORRECTLY DESIGNED OVERFIRE AIR SYSTEM.** This system must also be readily adjustable, and must introduce air in such manner as to assure early and thorough mixing of overfire air with the combustible gases in an optimum air/fuel ratio. It should induce circumferential flow for maximum gas combustion retention time and turbulence.
5. **A REASONABLY AIRTIGHT BURNER SHELL.** This is necessary to control the introduction of overfire air and to maintain high ignition temperatures.

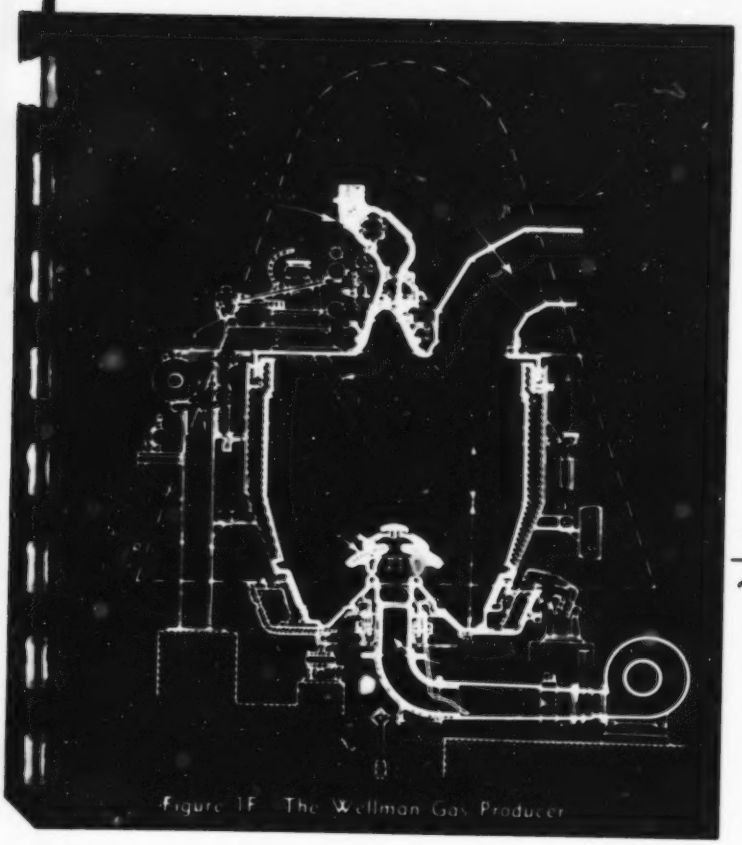
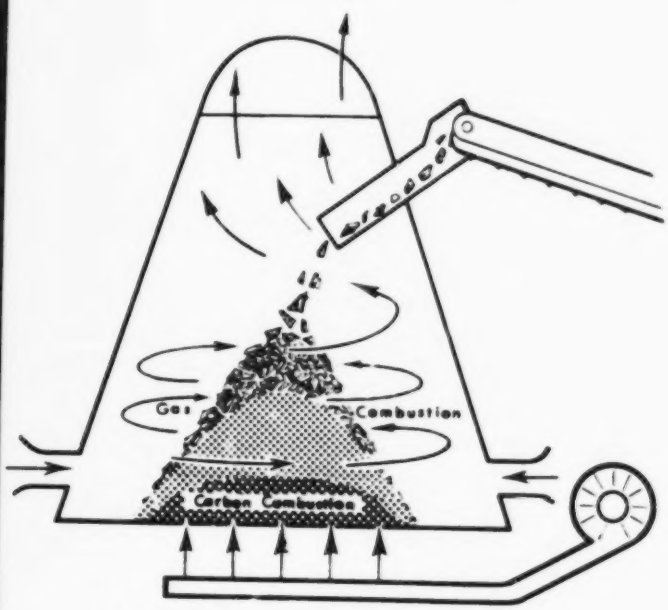


Figure 1F The Wellman Gas Producer



A wigwam waste burner combines the features of a gas producer and a gas combustion chamber. With careful attention to details of design and construction, it can be made to perform as an efficient combustion device.

Figure 1G

6. **CORRECT METHODS OF FUEL INTRODUCTION.** Fuel must be introduced to the fuel pile from above at a near-uniform rate and in a manner which will preclude its entrainment in the rising combustion gas stream.

7. **CORRECT ADJUSTMENT.** The underfire air system must be periodically readjusted to provide the correct carbon combustion rate. The overfire air must be periodically readjusted to assure an optimum ratio of air to combustible gas. A pyrometer to record the exit gas temperature is a necessity for correct adjustment.

8. **ADEQUATE MAINTENANCE.** This is principally a matter of ash and clinker removal. Daily removal of clinker from the underfire outlets and weekly removal of all ash and clinker from the burner is good practice.

An initial survey of the fuel characteristics and delivery rates may indicate their inadequacy and the advisability of investigating (a) alternative methods of disposal, (b) reducing the size of the burner, (c) part time burner operation from a wood waste stockpile, or (d) alteration of the fuel's physical characteristics (Example: reduction of coarse materials with resaw or hog).

If the survey (See Chapter 2) indicates a possibility that the fuel quality and delivery rate may be adequate for the existing burner, or even for a burner of smaller size, the best solution may be to proceed with a modification program. After steps 3 through 8 have been accomplished and the results observed, a correct assessment of burner size can be made. If it is then found that gas and suspended particle ignition temperatures cannot be maintained (See Chapter 6) the burner may be reconstructed to a smaller diameter, or may be replaced with a smaller burner. (Many good used burner are available at nominal cost).

HOW MUCH WASTE DO YOU BURN?

Before proceeding with the design and construction of any aspect of a wigwam burner modification program, it is essential to first know the actual rate at which fuel will be delivered to the burner. The correct design of the underfire and overfire air systems as well as the correct size for the burner enclosure itself are based on the rate at which fuel is to be consumed.

Experience has shown that few mill operators can estimate the fuel delivery rate with the degree of accuracy needed. It must be actually measured. The alternative to actual measurement is to start with a guess and proceed on a "cut and try" basis. This approach has limited chance of success, usually consuming more time and money.

A bit of ingenuity may be required to devise the method of measurement that best suits a given installation, and some expense may be involved. It may even be necessary to "jury-rig" a means of temporarily diverting the material from the conveyor. Whatever the method, arrive at a number that reflects the **maximum sustained rate** at which wood waste will be delivered to the burner. This all-important number expresses the delivery rate in **pounds per hour.**

The following are some suggested methods of measurement, any of which should be applied during a representative maximum production run.

a) Divert the material from the burner conveyor to a truck for a timed interval, preferably the time required to fill the truck. Weigh the loaded truck and subtract from this its unloaded weight. The difference divided by the number of minutes required to fill the truck is the material delivery weight per minute. Multiply this by 60 to obtain the rate in pounds per hour.

Total Weight of material in truck ÷ **Time** required to load (minutes) × 60 = **Rate** (pounds per hour)

b) Arrange for a typical production run at start-up Monday morning. Back a truck into the burner and time the interval it takes to fill. Weigh and calculate pounds per hour the same as for a), above. (If burner door is too small, transfer material to truck with bucket loader, chute or wheelbarrow.)

c) Count the number of conveyor flights that pass a given point in one minute. Arrange with production personnel for a representative run immediately before noon shutdown. During this run, stop the conveyor and collect the material from as many flights as possible for weighing. Make a note of the number of flights from which the material was taken.

The total weight divided by the number of flights from which the material was taken gives the average weight per flight. Multiply the average weight by the number of flights that pass a point in one minute to determine the weight per minute. Multiply by 60 to convert to pounds per hour.

Total Weight of material weighed ÷ **Number of Flights** × **Conveyor Speed** flights per minute × 60 = **Rate** lbs. per hr.

2. OVER-FIRE AIR SYSTEMS . LAWS OF AIR MOTION

The design of the overfire air system can be the determining factor as to whether or not a burner is capable of efficient combustion. Some of the most critical design considerations might seem at first glance to be of minor effect and are thus easily overlooked, so it is important that they be understood. This understanding is principally a matter of knowing how air in motion behaves. For purposes of clarity and brevity, the following discussion will present only those concepts which apply to the problem at hand.

AIR MOVES DUE TO A PRESSURE DIFFERENCE

First of all, air moves from one place to another because of a difference in pressure. It doesn't move because something is pulling it, but because it is being pushed. For this reason, we would probably be better off if the term "suction" had never been invented.

When we inhale a breath of air, what we are actually doing is using our chest muscles to reduce the pressure within our chest cavity to something less than atmospheric pressure, so that atmospheric pressure will push air into our lungs. Conversely, when we exhale, we increase chest pressure to something greater than atmospheric pressure so the air will flow out. The movement of the air, in or out, is governed solely by the **difference** in pressure that we create with our chest muscles. When we wish to inhale, we produce a "negative pressure" in our lungs (less than atmospheric pressure). When we exhale, we produce a "positive pressure."

PRESSURE NEEDED TO OVERCOME FRICTION

If we need to breath rapidly, our chest muscles must work harder, because we must increase the pressure difference so that the air will move faster through our nose and throat. As we breathe still more rapidly, we find that our nose creates too much friction, and we must open our mouth to provide additional air passage.

This is due to a fundamental law which applies to a given air duct system: that **friction increases as the square of the velocity.** In other words, if we double the velocity, friction increase 4 times; if we increase the velocity 3 times, the friction will increase 3 x 3 or 9 times.

PRESSURE NEEDED TO PRODUCE VELOCITY

Another fundamental law will explain why our chest muscles must work so much harder when we breathe rapidly, and this one is quite startling: that **power required increases as the cube of the velocity.** This means that doubling the velocity requires 2 x 2 x 2, or 8 times the power.

It may seem inconsistent that 8 times as much power is needed to produce 2 times the velocity when friction increases only 4 times. This is because air has weight, and energy is needed to accelerate it from standstill to a given velocity, just as with our automobile.

Having weight, air in motion has momentum, or inertia, and tends to keep going in a straight line until slowed by friction or by impact with a surface. Because air is fluid, it can be deflected from its direction of travel to some other direction. In so doing, some of its velocity energy will be imparted to whatever caused the deflection. You can feel this velocity energy, or pressure, when you hold your hand in front of a fan.

The difference in pressure which causes air to move from one place to another, or to increase its velocity, is termed "static pressure."

The pressure which air in motion exerts due to its momentum is termed "velocity pressure."

An automobile tire inflated to 30 pounds pressure exerts an outward, or "static pressure" against the wall of the tire of about 45 pounds per square inch, but atmospheric pressure is about 15 pounds per square inch, so we read the **difference** in pressure with a gauge as being 30 pounds per per square inch. There is no air in motion, so there is no velocity pressure, only static pressure. If the tire is punctured, static pressure in the tire pushes air out through the opening with considerable force. This 30 pound difference is then expended in overcoming the resistance in the opening, and in accelerating the air stream to a high velocity. In effect, most of the static pressure in the tire is converted to velocity pressure in the moving airstream.

PRESSURE MEASURED WITH MANOMETER

Because the differences in pressure with which we will be concerned in designing such things as an overfire or underfire air system ar quite small compared to the pressure in an automobile tire, we must use a measuring device which is more sensitive than a tire pressure gauge. The customary device is called a "manometer," and it measures in terms of the height that a given pressure difference will cause a column of water to rise in a tube. This height is measured in inches, hence the term "inches water gauge." In practice, the words "water" and "gauge" are usually dropped, and the terms "inches static pressure" or "inches velocity pressure" used for brevity.

Now let's apply the principles of air motion to the design of an overfire air system. First, a review of the gas combustion concepts.

EARLY MIXING ASSURES BEST COMBUSTION

In Chapter I it was shown that as the producer gas is emitted from the fuel pile, it must be thoroughly mixed with the correct amount of air to provide a good combustible mixture. If too little air is provided, there will not be enough oxygen present to complete the combustion process. On the other hand, too much air will both cool and dilute the gas-air mixture so that it will ignite only partially, if at all.

At the moment the producer gas issues from the fuel pile, it is concentrated and quite hot. Unfortunately, the gas subsequently loses heat by radiation to the cooler surfaces presented by the burner shell and the newly introduced fuel at the top of the pile. It also becomes both diluted and cooled by the water vapor issuing from the upper part of the fuel pile.

The best conditions for ignition thus occur when air is mixed with the gas as soon as possible after it emerges from the fuel pile. Gas combustion is then observed as a series of compartively short, intense flames that are concentrated alongside the lower portion of the pile. When this condition is achieved there is an added bonus in that a zone of gas combustion is then created below and separate from the fuel drying zone. The moisture being driven from the fresh fuel at the top of the pile then mixes with the burned gases and does not dilute the combustible gases. This is an especially important consideration with fuels of high moisture content.

CIRCUMFERENTIAL FLOW AIDS MIXING

The key to early mixing and ignition is through "circumferential flow" or rotation of the gases within the burner. This can be induced by introducing overfire air as a series of high velocity jets all directed in a like direction tangent to the fuel pile. The momentum (velocity pressure)) of the overfire air represents energy that is imparted to the gases inside the burner causing them to flow in the same direction as the jets. The higher the jet velocity, the higher will be the induced velocity of the rotating gas-air stream.

"Circumferential flow" results in the horizontal circulation of air around the fuel pile. The producer gas is then mixed with air by a **blending** action immediately after it issues from the pile, so that the conditions favorable to ignition are reached quite quickly. The much desired **zone of gas combustion** around the lower part of the fuel pile thus depends upon a strong horizontal flow pattern created by circumferential flow.

Of the various types of inlet ports in common use, most produce circumferential flow in some degree. They discharge in a tangential, counter-clockwise direction, and rely on the difference in pressure created by stack effect to cause air to move through them into the burner.

STACK EFFECT PROVIDES THE POWER

Because the natural draft type of overfire air inlet port depends upon stack effect to produce jet velocity and thus induce circumferential flow, it is important that we understand this source of power and how it can best be put to use.

"Stack effect" results from the column of hot gases inside the burner having less density, and thus less weight than the air outside the burner. The difference in weight is observed as a difference in static pressure. As the static pressure outside the burner (atmospheric pressure) is greater than that inside, air is forced inward through the overfire air ports. As the pressure inside the burner is less than atmospheric it is referred to as a "negative pressure."

The pressure difference increases as the gases increase in temperature. It also increases as the height of the column of hot gases contained within the burner shell is increased. As an example, the negative pressure as measured at the base of a 60 foot burner is approximately twice as great as it is at the base of a 30 foot burner. It also becomes progressively less at elevations above the burner base until it is relatively non-existant near the top.

A tight burner shell will develop the greatest pressure difference because a leaky burner admits uncontrolled air which cools the gases so that their average temperature is reduced. An opening located near the base of the burner where the negative static pressure is greatest will admit more air than the same sized opening farther up the side. Because we must introduce overfire air in a controlled amount and in a manner that will produce maximum circumferential flow, a tight burner shell is mandatory.

LEAST FRICTION MEANS HIGHEST VELOCITY

The pressure difference due to stack effect works for us in two ways: (a) to overcome the resistance of our inlet ports to the flow of air through them, and (b) to accelerate the air from standstill to its velocity leaving the ports. It follows then, that the less of our available pressure difference we use in overcoming resistance, the more we will have available for imparting velocity to the overfire air.

Our goal should be to reduce the losses in our inlet ports to a practical minimum, so that the available pressure difference can be utilized to produce the maximum possible velocity pressure.

AIR VELOCITY TABLE

Velocity pressures (inches of water) and their corresponding air velocities (ft. per min.)

V. P.	VEL.	V. P.	VEL.
.04	798	.28	2118
.06	984	.30	2196
.08	1134	.32	2268
.10	1266	.34	2334
.12	1386	.36	2406
.14	1494	.38	2472
.16	1602	.40	2532
.18	1698	.42	2592
.20	1794	.44	2658
.22	1878	.46	2718
.24	1962	.48	2772
.26	2040	.50	2832

Figure 2 A

If it were possible to design an inlet port without any losses, all of the stack effect, or pressure difference, would be available to impart velocity to the overfire air. As an example, let's assume that we have a pressure difference of 0.16 inches water gauge. From figure **2A** it will be seen that this would produce an air velocity of 1602 feet per minute if we had no losses.

However, it is impossible to design an overfire air inlet without resistance. We must provide means of dampering the air volume, and of directing the overfire air so as to best induce circumferential flow. These devices must, by their nature, introduce losses. However, by exercising care, we can keep them to a minimum. The losses fall into two categories: friction losses and dynamic losses. First, let's assume that our overfire air inlet resembles a short duct about 3 feet long and see how much friction is involved.

Friction results from air moving along a stationary surface and is thus greater for a rectangular duct than for a square one, and greater for a square duct than for a round one, because there is more surface area enclosing the same cross-sectional area. Also, one large duct 4 feet square obviously has much less surface in contact with moving air than 16 ducts 1 foot square, although they have the same total cross sectional area, 16 square feet. Actually the 16 small ducts present 4 times as much surface area

A few large ports are thus better than a number of small ones. Round ports would be better than rectangular, but for practical construction reasons they will not be considered

For example, if we have available a pressure difference of 0.15", friction loss would represent 10% in a 20" x 6" port, 4% in a 24" x 12" port, and 3% in a 30" x 18" port. Thus the friction loss in a small port can be significant, but there doesn't seem to be much saving in friction with ports much larger than 24" x 12".

Now that we have examined the losses due to surface friction, let's look at another type of loss that invariably occurs at an air inlet.

DYNAMIC LOSS EXCEEDS FRICTION LOSS

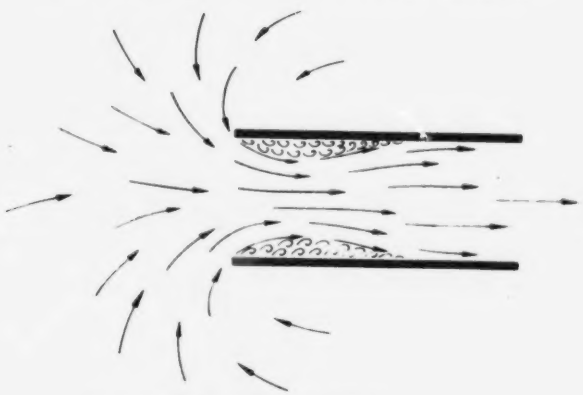
The major loss in those inlet ports in common use is not due to surface friction but to "dynamic loss." This type of energy loss is characteristic of eddying or turbulent flow and is present when air in motion is made to change either direction or velocity.

To illustrate, let's examine what happens when air enters the open end of a pipe in which a negative pressure exists Figure 2B

Air approaches the opening from all directions at velocities which increase as the air stream converges. Because air which approaches from the sides must make the greatest change in direction as it approaches and enters the pipe, its momentum forces all of the approaching air to converge, and even to continue to converge after it has entered the pipe. In a round pipe, the point of maximum convergence, called the "Vena Contracta" is about one-half pipe diameter downstream from the end of the pipe. The air stream at this point occupies about 60% of the area of pipe. The remaining 40% is an area of low pressure and turbulence. The dynamic loss in such an entrance is quite high and is due both to changes in direction and velocity.

CONVERGING AIR FLOW AT A ROUND PIPE ENTRY

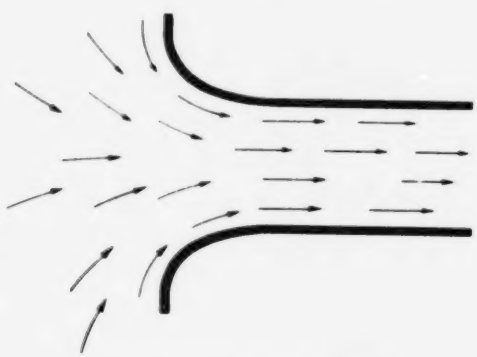
RAW EDGED CIRCULAR ENTRY



CONVERGING AIR FLOW IN A RAW EDGED CIRCULAR ENTRY

Air entering the end of a raw edged round pipe converges within the pipe, creating an area of low pressure and turbulence. The dynamic losses in such an entry are quite high and are due to changes in direction and in velocity.

FORMED CIRCULAR ENTRY



CONVERGING AIR FLOW IN A BELLMOUTH ENTRY

A high efficiency entrance is formed so that air converges smoothly and at uniformly increasing velocity. in laboratory applications, carefully designed and polished circular nozzles of this type are used which have efficiencies of over 99%.

Figure 2 B

By contrast, the most highly refined entrance is formed so that air flows smoothly as it enters and no area of turbulence occurs. In laboratory applications, carefully designed and polished circular nozzles of this type are used which have efficiencies of over 99%.

However, published data on the design and performance of a formed entrance applies only to round pipe configurations. For practical reasons this isn't of direct application in the design of an overfire inlet, because of cost and because we must incorporate a means of volume adjustment. A circular, formed entrance must be constructed by metal spinning, die forming, or casting techniques, and the performance advantages would be lost unless complex dampering methods were also constructed.

FORMED ENTRANCE CAN BE ADAPTED

The problem is thus to adapt the principles of a formed entrance to a rectangular duct and thereby improve its efficiency. This could be accomplished by constructing a four-sided bellmouth with mitered corners, but such a design might be considered somewhat expensive. Also, the installation of a damper that will not interrupt the smooth flow of air poses some problems.

One solution is to modify the four-sided bellmouth as shown in Figure 2C. This design provides the advantages of a formed entrance on its longest sides, which represent most of the perimeter. Then by extending the short sides to a point where the approach velocity is low, we can get by with a shorter radius along their edges, because a change in direction is of less consequence at a lower velocity.

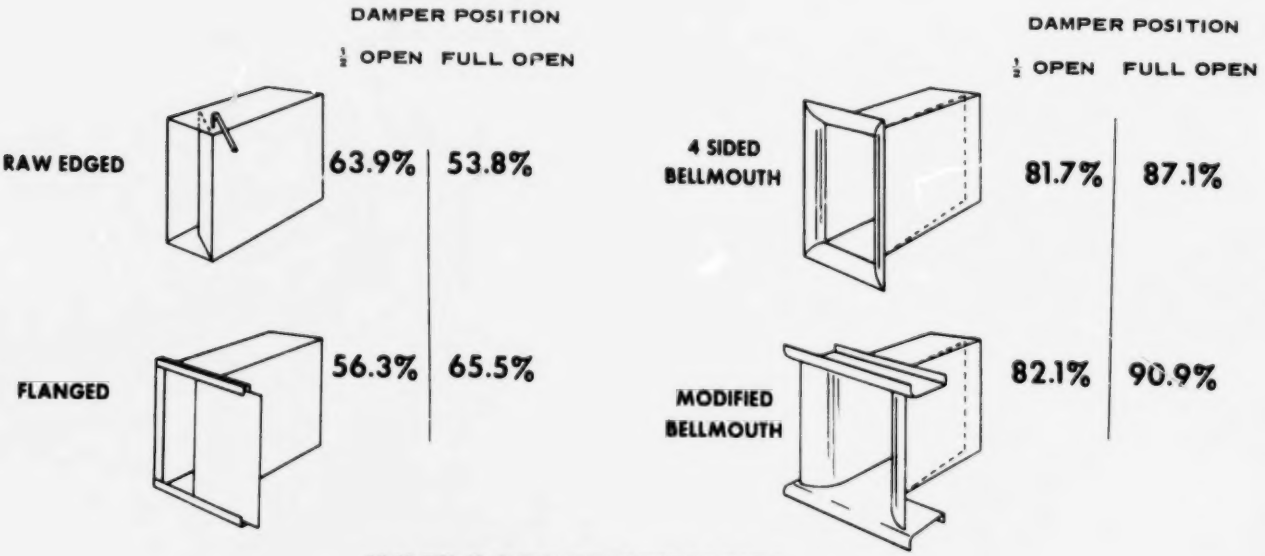
The problem of providing a means of volume adjustment can be solved by the use of a long damper blade with which the width of the discharge opening can be changed while retaining the low-loss advantages of a convering taper. By incorporating one side of the formed entrance as an extension of the damper blade, smooth flow is assured for any position of the damper.

The resulting design is relatively simple to construct, can be cut from standard metal sheet sizes with little waste, and will reduce losses to a practical near-minimum.

LABORATORY TESTS VERIFY EFFICIENCIES

A laboratoy evaluation of the actual losses in various types of inlet ports has shown their comparative effectiveness under simulated field conditions. Tests were conducted on two types of inlets in common use, on a four-sided bellmouth inlet, and on the modified bellmouth inlet described above. From the test data, average efficiencies have been developed for the four types through the range of 0.05" to 0.25" pressure difference. These are as shown in Figure 2D.

The term "efficiency" as used here refers to the efficiency with which static pressure is converted to velocity pressure, and is the percentage that the conversion approaches ideal, or 100%. We have used velocity pressure as the criteria, because it is the force which is effective in producing circumferential flow.



INLET PORT EFFICIENCIES

EFFICIENCIES WITH WHICH DIFFERENTIAL STATIC-PRESSURE IS CONVERTED TO VELOCITY PRESSURE.
(AVERAGE FOR THE RANGE OF 0.05 THRU 0.25 INCHES DIFFERENTIAL PRESSURE.)

Figure 2 C

The effects of inlet efficiencies on the actual air volumes that will be admitted through 12" x 24" ports are shown graphically in Figure 2D. It will be noted that at a pressure difference of 0.15", an ideal port with no losses would admit 3100 cfm. By comparison, the modified bellmouth port would admit 2975 cfm and a raw edged entry port 2300 cfm. This means that 12 modified bellmouth ports would admit the same air volume as 16 with raw edged entrances.

Discharge velocity patterns for the flanged entry and bellmouth entry configurations are shown graphically in Figure 2E. It will be noted that with dampers one-half open, the jet velocity for the bellmouth entry is 70% greater than for the flanged entry.

The advantage of a high jet velocity may be illustrated by an example. When you are stirring a bucket of paint, the paddle must be moving faster than the paint if the paint is to continue to rotate in the bucket. Similarly, it is possible to induce a gas flow of 900 feet per minute with a jet velocity of 1200 feet per minute, but it is impossible to do so with a jet velocity of only 800 feet per minute. The induced velocity will always be something less than the jet velocity.

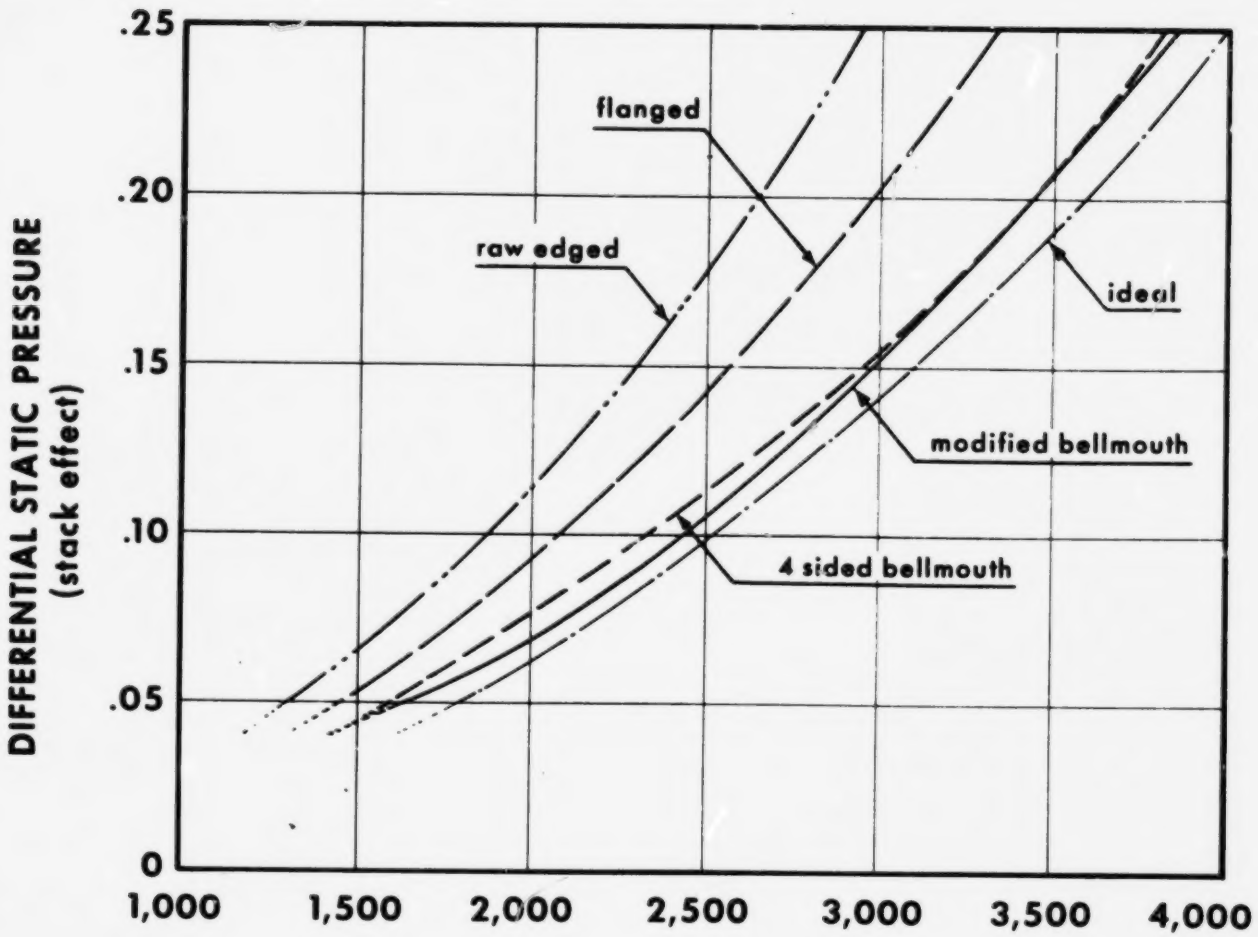


Figure 2 D

DISCHARGE ANGLE ALSO IMPORTANT

The angle at which the jets discharge into the burner also has a marked effect on the circumferential flow velocity they are able to induce. If the jets are directed too nearly parallel to the shell, much of their energy will be lost in friction with the shell. This is especially true if the burner has an inside structural frame. At the opposite extreme, if they are directed too far inward toward the fuel pile, circumferential flow can be reduced to the extent that the flow pattern will be dictated by the thermal rise of the hot gases rather than by the jets.

It appears that best performance is obtained when the inlet port ducts are mounted horizontally at an angle of 45° with the burner shell, and with the bottom of the ducts at an elevation above the base of approximately 1 foot for each 10 feet of burner diameter.

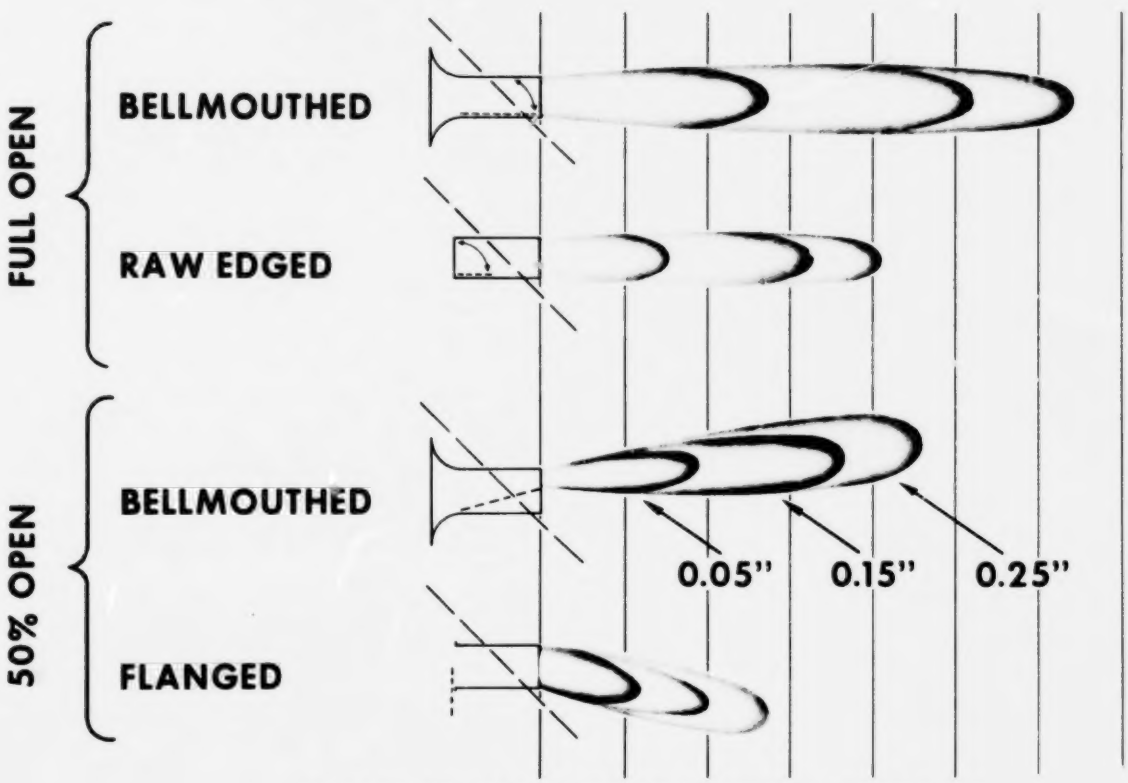
The overfire air ports supply the oxygen to burn the producer gas. They must be matched to the combustion rate, plus at least 25% to take care of an overload, plus another 25% because under the overload condition a greater amount of air may be needed for cooling to avoid the risk of damaging the burner.

STACK EFFECT ABSENT WHEN NEEDED

The above discussion has been confined to the principles that apply to the introduction of overfire air by means of natural draft overfire air inlet ports wherein the overfire velocity is used to induce circumferential flow.

While this method has several advantages, including those of simplicity and cost, there are many possibilities for improvement in design, primarily by the use of blowers, with or without automatic control.

The principal shortcoming of the natural draft port is its dependence upon stack effect as a source of power. Stack effect is dictated by the average temperature in the burner, increasing as the temperature increases. As a result, circumferential flow is least when it is most needed, during start-up and when combustion is sluggish. Also, as may be seen from Figure 2E, the overfire air ports have their greatest jet effect when their dampers are full open. This means that maximum circumferential flow, which aids combustion, can be obtained only by admitting an excess of overfire air, which hinders combustion by its cooling and diluting effects.



COMPARATIVE JET VELOCITY PATTERNS
For Various Inlet Port Types At Differential Pressures of 0.05", 0.15" and 0.25"

Figure 2 E

BLOWERS OFFER AN ALTERNATIVE

By contrast, blowers may be selected for any desired conditions of volume and pressure, and perform independently of variations in stack effect. The following are some suggested arrangements for mechanically powered overfire air systems.

1. A series of blowers which are sized for the minimum volume of overfire air to ever be needed, discharging overfire air continuously through tangential high velocity jets. Supplemental overfire air is introduced through conventional natural draft ports. The blower powered high velocity jets are designed to induce the much needed circumferential flow during start-up or sluggish conditions, and provide additional energy during normal operation.

2. A series of blowers and natural draft ports arranged as in (1) above, except that the blowers have their inlets connected to the burner shell so as to handle all recirculated air from within the burner. They can, by this method, be sized for larger air volume and lower pressure characteristics than in (1), but must be suitable for high temperature operation. The overfire fresh air volume is all introduced through the natural draft ports.

3. A series of high volume, high temperature blowers, sized to deliver the total volume of overfire air, with an inlet damper arrangement which permits proportioning of fresh and recirculated air through the complete range from 100% fresh to 100% recirculated. This system is readily adaptable to automatic control of the fresh air volume. No conventional natural draft ports are needed except for standby in case of power failure.

4. Any of the above arrangements substituting a single blower and comprehensive duct system for the multiple blower and duct systems.

5. This is a possible adaptation of arrangements No. 2, 3, or 4 with recirculated gases taken from the burner exit instead of from near the base. This is actually a method of preheating the overfire air with heat recovered from the exit gases. It would require careful design, however, due to the temperature and contamination of the exit gases.

SUMMARY

To summarize, the principal considerations in the correct design and performance of the gas combustion phase of a wigwam waste burner are as follows:

1. The burner shell must be reasonably airtight to assure that all overfire air is introduced in the most effective manner and in a controlled amount. The goal should be to eliminate parasitic leakage which cools the fire, disrupts circumferential flow and reduces the stack effect.

2. The overfire air inlet ports must be efficient, adjustable, and properly sized for the rate of fuel combustion and the height (stack effect) of the burner. They should make maximum use of stack effect to induce circumferential flow.

3. The use of motorized blowers to assure circumferential flow during start-up and sluggish combustion offers an alternative to reliance on stack effect. Many different arrangements are possible, some of which can be adapted to automatic control.

3. UNDER FIRE AIR SYSTEMS . FANS . DUCTS . OUTLETS

The underfire air system supplies the oxygen to burn the carbon in the base of the fuel pile. The more oxygen we supply, the faster the carbon will be converted to carbon dioxide, carbon monoxide and ash, and the more heat will be generated to manufacture new carbon from the distillation process. The underfire air volume thus governs the combustion rate, and should be sized to match the rate at which fuel is delivered to the burner, plus at least 25% to take care of emergencies.

Such an emergency can occur if the operator fails to check the burner periodically and the fuel pile becomes too large. He must then increase the combustion rate to above normal for awhile to bring the pile down to normal size.

CHANNELING AVOIDED BY DISPERSION

A critical requirement of the underfire air system is to assure that the rate of carbon combustion is uniform throughout the base area of the fuel pile. This means that an equal volume of air must be supplied to each portion of the base area.

When air is supplied to one sector of the fuel pile at a rate faster than the carbon can combine with the oxygen in the air, an excess of oxygen is present in the gases traveling outward through this sector of the fuel pile. This excess oxygen mixes with the produced gases within the fuel pile, as the gases are generated. The combustible mixture then ignites within the pile, and a blowtorch or volcano effect is created in this sector. The effect is self-perpetuating because the intense heat from the burning gases causes much more rapid distillation of fuel along their path, enlarging and maintaining an open channel. Also, the gases expand as they burn, and the resulting increase in their velocity has a scouring effect, conveying particles outward in a shower of sparks and unburned carbon.

The worst example of this condition can be observed when air is introduced through a single outlet at the center of the fuel pile. The result is a simulated volcanic crater, surrounded by a circular ridge of partially burned material to which new material is continuously added by the eruption. Fresh fuel from the conveyor drops into the crater causing a recurrent cycle of smothering and burnthrough, accompanied by clouds of black smoke. Circumferential flow is almost entirely lost. The smoke, flame and suspended particles travel in a near-direct path to the top of the burner and out.

Even with a uniform and well dispersed underfire air distribution system some channels can be observed, but they are mild in intensity and very little gas combustion occurs within the fuel pile unless the total underfire air volume is excessive.

Ideally, the only combustion to be observed is that of the producer gas burning outside the fuel pile. The only evidence that fuel is being consumed within the pile is that the pile grows no larger even though new material is continuously added to the top. The observed effect is as though material were being taken from the inside bottom of the pile at the same rate it is being added at the top. This effect can be attained with correct design and operation.

The key to correct underfire air system layout is uniform dispersion of the underfire air volume throughout the base area of the fuel pile.

BEST LAYOUT PROVIDES MANY OUTLETS

Perhaps the best underfire air distribution system would incorporate a large grate covering the floor of the burner to a diameter of approximately 5 feet less than the base diameter of the pile. The cross tunnel and grate system found in some of the older burners is a near-approach to a complete grate, especially if it has diagonal grates between the cross grates. To convert a tunnel system to an efficient forced air system usually requires only that the exposed grate area outside the fuel pile be blanked off, the tunnel ends be fitted with air-tight closures, and a blower be installed so as to discharge into the tunnels. If there are no diagonal grates they should likely be added, as no point in the base of the fuel pile should be more than three feet from a supply of underfire air.

In the absence of cross tunnels, the effect of a large grate can be simulated by a number of individual outlets arranged in polka dot fashion, so that each provides air to a small area. Experience has shown that these should be spaced a maximum of 5 feet apart, and that each should supply a maximum of 300 cubic feet per minute (cfm). Four foot spacing and 200 cfm per outlet are better design figures to use, especially if the fuel is predominantly fine, because the tendency to channel is greater in a more compact fuel pile.

As to type of outlet, a number of designs are in common use, with varying degrees of success. A good outlet should possess the following features:

1. Good dispersion throughout the area served. It should be a good "diffuser" and not discharge in a concentrated jet. Remember that it is a substitute for a flat grate approximately 4 feet square.
2. Ability to withstand high temperatures. Self-cooling by wiping action of the supply air can prolong life.
3. Freedom from plugging by clinkers or ash.
4. Strength to withstand blows from heavy falling pieces of wood.
5. Minimum obstruction to ash and clinker removal operations.
6. Ease of installation, servicing and maintenance.
7. Low cost.

CORRECT ENGINEERING MEANS LEAST COST

Unlike the overfire air system which utilized stack effect to produce air flow, the underfire air system utilizes a motor driven blower to create a pressure difference and thus cause air to flow through a duct system. The duct system is more complex than for the overfire system, but the same rules of air motion apply.

In designing the overfire system, we were limited to the pressure difference that stack effect could produce, which amounted to only a fraction of an inch static pressure. In designing the underfire system, this aspect of the design is within our control. With a blower we can overcome resistance by producing any reasonable pressure difference that we may wish.

There are a number of possibilities in the arrangement of the duct system serving the outlets. Individual preference for a given arrangement will usually be dictated by personal opinion as to which will involve the least cost. Cost comparisons should be made, however, on the basis of systems that are correctly engineered. Often a system that appears at first glance to be less expensive may not perform as anticiapted and may require expensive remodification. There is no need to guess. The engineering design methods are at hand to design a system that will perform as predicted.

Least cost will result from a system design in which all components are matched to the capacity requirements, in which frictional and dynamic losses are held to a practical minimum, and in which a good compromise is reached between first cost and operating cost.

The compromise relates primarily to motor horsepower vs. duct size. Smaller ducts are cheaper, but their increased friction demands more blower horsepower. Remember that if we provide ducts half as large, we then have 2 times the velocity, 4 times the friction, and 8 times the horsepower requirement. Not only are larger motors more expensive but the V-belt drives, wiring and starters are also more expensive. Also, first cost is only part of the story. Additional power consumption is a continuing penalty.

CONVENTIONAL FITTINGS SIMPLIFY DESIGN

Of the various methods that are available for sizing the pipes in a duct system, that more commonly used is known as the "equal friction method." It is quite simple to use, insures against needlessly oversize or restrictively undersize ducts, and assures that system performance will be as anticipated by its designer.

Almost any duct arrangement will work if it is properly designed. Simple, conventional layouts are usually less expensive however, and require less expertise in the way details are handled. There is a definite relationship between cost and the number of fittings required, so the layout should be made with an eye toward reducing the number of tees, elbows and transitions to a minimum.

Remember that dynamic losses occur whenever air in motion must make a sudden change in direction or velocity. Good practice in system and duct fitting design is to avoid sudden changes in direction as much as possible, and if this principle is adhered to the design of an efficient system becomes quite simple. By contrast, unconventional layouts can involve details which are difficult to design correctly, expensive to construct, and sometimes impossible to calculate in terms of their air flow characteristics.

Figure **3A** shows several examples of good and bad practice in duct construction. It will be noted that abrupt changes in direction are to be avoided, and that the best fittings also avoid rapid changes in total cross-sectional area (velocity). Of the four types of fan discharge connections shown, only (a) should truly be considered "best practice." The performance of the fan itself is adversely affected unless the discharge duct is a straight section for several duct diameters in length preceding an elbow that turns in a direction opposite to that of the fan scroll.

RADIAL BLADE FAN BEST SELECTION

Accepted terminology in the field of fan design is as shown in Figure **3B**. Of the types illustrated, the radial blade centrifugal fan is best for use in an underfire air system, with the backward curved centrifugal running a close second. The radial blade fan has the perferable characteristic of developing more pressure when partially plugged grates restrict flow.

Some marine type vane-axial fans are in use on underfire air systems, and it is possible to apply them with a degree of success if they are of the correct size and performance characteristics to match the system design. Unfortuniately, they exhibit efficient performance only within a narrow range of capacity. When this capacity (air volume) is reduced, as by grate plugging or by dampering, the fan blade "stalls." When it "stalls" its performance becomes unstable and it develops less pressure than at the volume for which it was designed. For this reason, vane-axial fans are normally used only on fixed capacity marine and industrial ventilation systems where they are carefully matched to the characteristics of the system.

MEANS OF VOLUME ADJUSTMENT NEEDED

The underfire air volume controls the combustion rate. This volume must be adjustable to control the size of the fuel pile and to compensate for differences in fuel quantity. The volume also must be reduced during start-up and until the fuel pile reaches it correct size. Having reserve capacity to take care of emergencies, the underfire air volume should normally be operated at about 80% of capacity, but the correct volume for "normal" operation can only be determined by experimentation. The need for adjustment is basic to efficient operation.

Several methods of adjustment are available, including variable speed control, inlet vane control, and several types of dampers. Of these, dampers are usually selected because of their simplicity and low cost.

The horizontal guillotine type of damper mounted at the fan inlet appears to be one of the more successful solutions. It consists of a rectangular steel plate which slides in horizontal grooves or channels across the fan inlet. For improved efficiency at wide open volume, the damper should be preceded by a converging taper or bell-mouthed inlet.

It is well to remember that most dampers provide the major portion of their volume adjustment as they approach complete closure. For example, a given damper may pass 50% of the wide open volume when it is only 20% open.

GOOD AND BAD PRACTICE IN ROUND DUCT FITTINGS

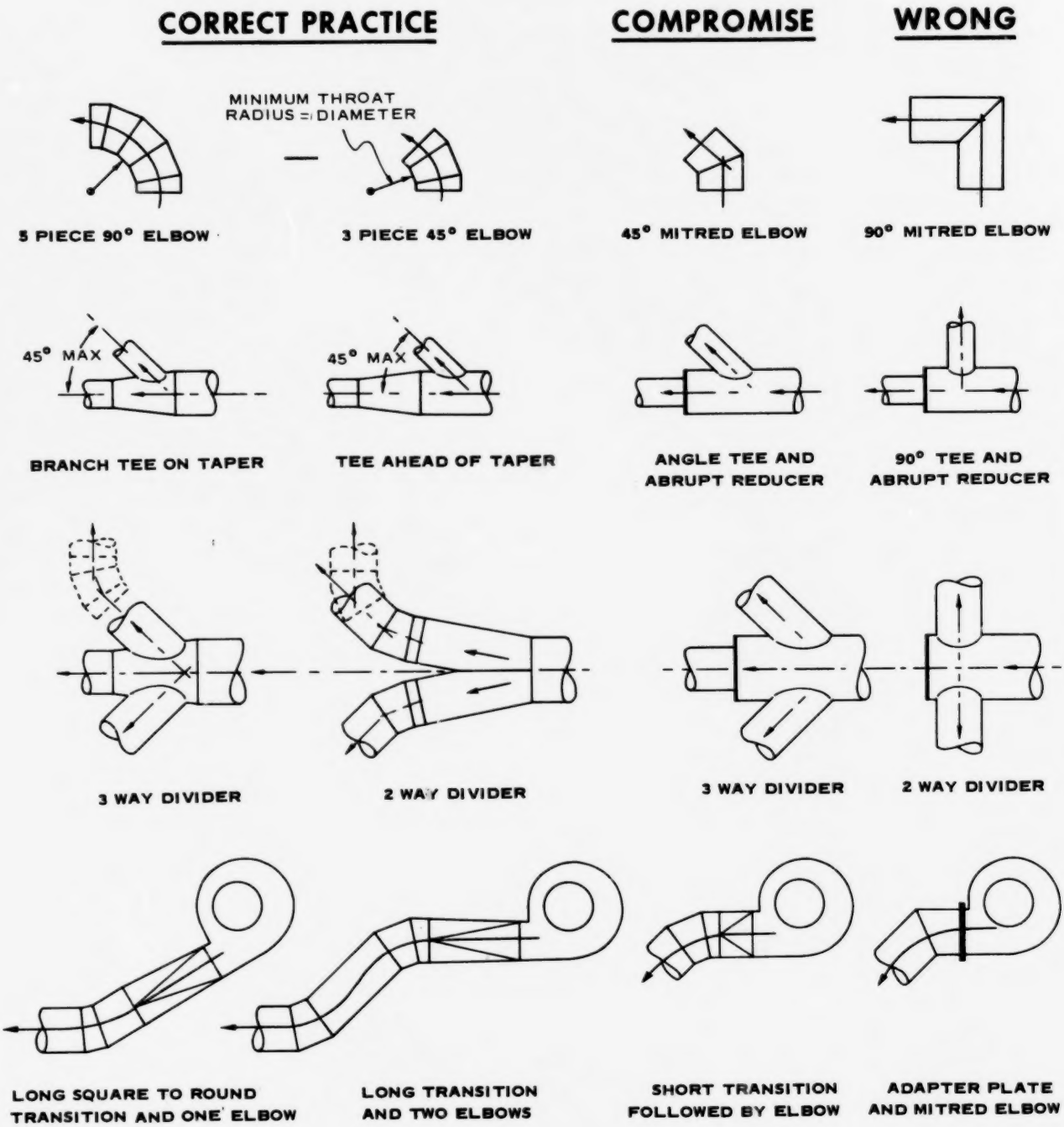
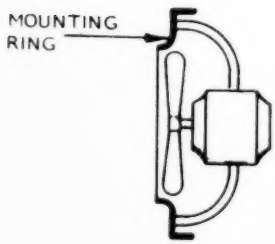
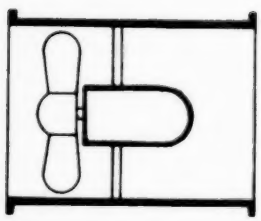


Figure 3 A

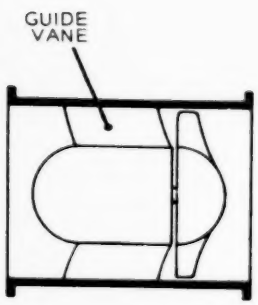
AXIAL FLOW FANS



PROPELLER

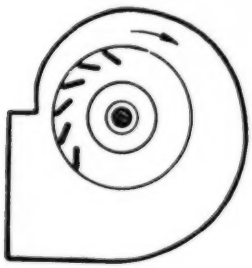


TUBE - AXIAL

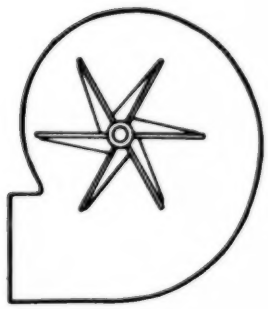


VANE - AXIAL

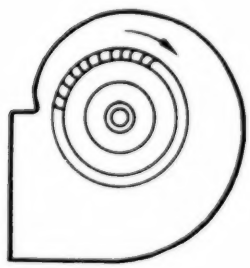
CENTRIFUGAL FANS



BACKWARD CURVED



RADIAL BLADE



FORWARD CURVED

FAN TERMINOLOGY

Figure 3 B

4. DETERMINING THE BEST SIZE FOR THE BURNER

The wigwam shaped metal enclosure which we must adopt as a combustion chamber was originally conceived to reduce the hazard of an open fire. For this purpose, it was important that it be sufficiently large to preclude its steel being overheated from a bonfire large enough to burn all the mill residues produced from cheap logs by inefficient methods. As mill capacity expanded, the enclosure even then often proved inadequate in size. Somebody apparently then found that the burner shell could be cooled by admitting air tangentially inside its skirt, and that the size of the bonfire could be reduced by blowing air at the fuel pile from underneath.

As logs became more expensive, attention was given to reducing the percentage of the log that was discarded, and to finding markets for the remaining residues. As a result, most burners are today too large for their fuel loading as normally operated, and almost all are too large when considered for modification as efficient combustion devices.

FUEL PILE DICTATES BURNER SIZE

In general, it may be anticipated that after installation of an efficient underfire air system, the size of the fuel pile will be reduced to approximately 1/3 its original diameter, depending upon the adequacy of the previous system. If there was no previous underfire system of any kind, the new diameter will be still smaller in relation to the original.

The size of importance because the best diameter for the burner will appear to be approximately 5' greater than the base diameter of the fuel pile. For example, a 20' diameter burner is about right for a fuel pile that is 15' in diameter. If the burner is too large, gas ignition temperature will be difficult to attain, and if it is too small, the metal shell and structure will be subjected to excessive temperatures.

An oversize burner shell imposes several penalties. Of these, one of the most important has to do with the loss of radiant heat energy.

OVERSIZE BURNER WASTES RADIANT HEAT

In simple terms, radiant heat is a form of energy transmitted by waves similar to the light general category of electromagnetic energy. For the purpose of this discussion, we will assume that the radiant heat rays originating from the combustion gas envelope travel in straight lines in all directions from their source until they meet an obstruction. If the obstruction has a polished metal surface, most of the rays will be reflected, but if the surface is dead black, most of the rays will be absorbed. As the inside of the burner shell must be classed as "dark", but not as "dead black", it both reflects and absorbs. Radiant heat energy that is absorbed by a surface will cause its temperature to rise, and it will then in turn become a source of radiant heat by re-radiation.

Because radiant heat energy travels in all directions from its source, its intensity diminishes quite rapidly with distance. The law that applies states that the intensity varies inversely as the square of the distance. For example, a perfect reflector located 2' feet from the flame would return only one-fourth the radiant intensity that it would at a distance of 1' foot. A burner that is 2' feet too large is a much less effective radiant reflector.

Actually the burner shell surface is a very poor radiant heat reflector and absorbs much of the heat that reaches it. This causes its temperature to rise and it in turn transmits heat by re-radiation to any surface that it can "see". This includes the newly introduced fuel. Here again, the inverse square law applies with the same rapidly increasing penalty for an oversize burner.

HEAT LOSSES REDUCE SHELL TEMPERATURE

Further penalties result from the additional heat dissipated to the surroundings from an oversize burner. We have stated that the shell "transmits heat by re-radiation to any surface that it can 'see'." This includes almost every possible surface outside the burner as well as outer space.

In addition to loss by radiation, heat is also lost to the outside air that wipes across the burner, especially when the wind blows, and heat is absorbed in evaporating water that falls on the burner when it rains. The net result is that each square foot of the burner shell is primarily a heat dissipator, so the less exposed area the better.

CIRCUMFERENTIAL FLOW ALSO REDUCED

Another penalty imposed by an oversize burner has to do with the overfire air system and its ability to produce circumferential flow.

The volume of overfire air required for optimum gas combustion is determined by the combustion rate, and is the same regardless of the burner size. Consequently the velocity energy in the overfire air jets is also approximately the same. If the burner is oversize, the same velocity energy must induce a greater volume of gases within the burner to rotate, with the result that the rotation is slower. The jet from a hose nozzle will induce very rapid rotation in a bucket of water, but it doesn't have much effect in a swimming pool.

UNDERSIZE BURNER OR OVERSIZE FUEL PILE?

On the other hand it is possible for a burner to be too small. The burner shell is then too close to the gas combustion flames which can even impinge on the shell. The metal enclosure then receives heat faster than it is dissipated and the metal temperature eventually reaches the danger point. It then starts to weaken, distort and buckle. Most burner failures appear to be due to actual flame impingement on the shell, as evidenced by buckling and distortion of the lower plates. The condition almost always appears to develop in burners with an inadequate, poorly maintained, or non-existent underfire air system.

Without adequate underfire air, the only oxygen available in quantity is at the surface of the pile, and consequently all combustion takes place at the surface of the pile. In order that the combustion rate can match the rate at which new material is delivered to the burner, the fuel pile must grow until sufficient material is exposed at the surface.

After an underfire air system is installed, the fuel pile will also reach a point of equilibrium at which the combustion rate equals the fuel delivery rate. Combustion is then much more efficient, however, and the size of the fuel pile will be considerably smaller.

FUEL CHARACTERISTICS AFFECT PILE SIZE

The size that the fuel pile will reach when the combustion rate equals the fuel delivery rate is also governed by the time required to distill the moisture and the volatiles from the wood and then to burn the carbon. A period of time is required for fuel to progress through these three phases. The length of time required varies with the amount of moisture in the wood and with the thickness of the pieces.

Before distillation of the volatiles can begin the moisture must first be driven out. Newly introduced, moist wood when subjected to heat will not reach a temperature of more than 212° (boiling point of water) until the moisture is driven out. Very little of the volatiles are distilled by the time this temperature is reached.

After the moisture is driven out and as a given piece of wood progresses downward through the fuel pile, it is subjected to progressively increasing temperatures and the volatiles are driven off. As was shown in Figure 1C the distillation process is complete by the time a temperature of 500° is reached and only carbon and ash remain.

The thickness of the wood is of consequence because wood is a good insulator. More time is required for heat to penetrate to the inside of a thick piece and distill its volatiles than for a thin piece. This fact is readily apparent in a burned out building with its structural timbers charred but still relatively intact.

DISTILLATION TIME VARIES WITH THICKNESS

Because carbon ignites at 640° and distillation continues to 500°, it is obvious that the carbon combustion phase can begin before the distillation phase is complete. In a thick piece of wood both phases occur simultaneously as heat progressively travels to its interior. This fact is visually evident in Figure 4A which shows what happens inside a piece of wood which is subjected to flame temperatures. Tests performed at the Forest Products Laboratory at Madison, Wisconsin, have shown that when Douglas fir is subjected to a temperature of 1500 degrees, the time required for carbonization is approximately 55 minutes for each 1½ inches of wood depth.

The time required for a piece to be reduced to carbon in the fuel pile of a wigwam burner is undoubtedly longer than in the tests because the material is not continually subjected to flame temperatures. Whatever the temperature pattern may be, the obvious conclusion is that the time requirement for thick materials can be considerably greater than for thin materials. Coarse materials will therefore result in a larger fuel pile than fine materials because the fuel pile must provide residence time for heat penetration. For example, a fuel that takes 4 hours to process will result in a fuel pile twice as large as that for a fuel that takes two hours.

When we say "twice as large," we refer to a fuel pile with twice the volume. Because the volume increases much more rapidly than the diameter, only about 25% increase in diameter is needed to provide twice the volume. The effect of fuel thickness on pile diameter is therefore not likely to require special consideration unless the fuel is composed of predominantly thick material.

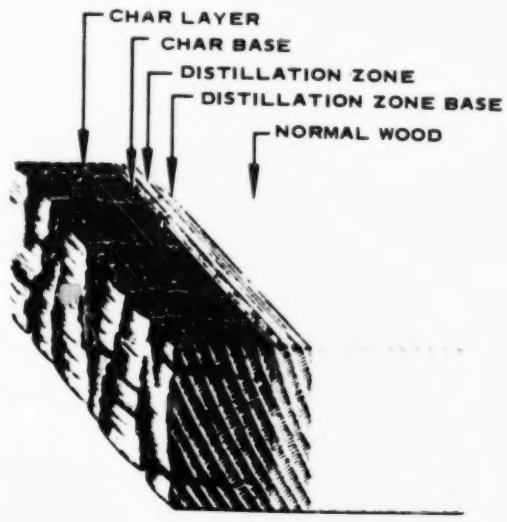


Figure 4A

When exposed to 1500 degree temperature at the surface, the Pyrolysis zone in a thick piece of Douglas fir travels inward at the rate of approximately 1½ inches every 55 minutes. Cracks in the carbon layer provide passages through which the volatile gases escape.

PROGRESSIVE DECOMPOSITION IN A THICK PIECE OF DOUGLAS FIR

SUMMARY

Almost all burners are oversize. An oversize burner is a poor radiant heat reflector. It absorbs most of the heat it receives and dissipates it to its surroundings.

Circumferential flow is more difficult to produce in an oversize burner because of the greater volume of gases which must be induced to rotate.

An undersize burner is marked by buckling and distortion of the lower shell plates and sometimes the structural frame, from excessive temperature. Usually the fuel pile has grown to such a size that only a narrow space exists between fuel pile and shell, and the shell is subjected to intense radiant heat if not actual flame impingement. The condition is usually due to an improperly designed, constructed or maintained underfire air system.

The size of the fuel pile determines the correct size for the burner enclosure. The size of the fuel pile is in turn governed by the rate at which fuel is delivered to it, and by the moisture content and average thickness of the material.

The size of the fuel pile is also governed by the adequacy of the underfire air system, but any approach to correct burner sizing must be based on the assumption that the underfire air system is also correct. Addition of a correctly designed underfire air system will usually bring about a considerable reduction in the size of the fuel pile.

Experience has shown that best burner performance is obtained when the burner diameter is approximately 50% greater than the base diameter that the fuel pile will reach under equilibrium conditions. The determination as to what the diameter of the burner should be can be based on the measured fuel delivery rate, or on the base diameter of the fuel pile as observed after installation and adjustment of a correctly designed underfire air system.

5. FUEL INTRODUCTION . METHODS AND PROBLEMS

For the wigwam waste burner to function in accordance with the destructive distillation concept, and in a manner that assures separation of the carbon and gas combustion phases, it is necessary that all fuel be delivered to the top of the fuel pile. Once the material comes to rest on the pile it can then progress through the various steps from drying to carbon combustion as planned and the requirements for efficient combustion can be controlled and predicted.

This is not to say that other methods of combustion, such as burning in suspension cannot be made to work. Many boiler installations are in operation which operate on the suspension burning principle quite successfully. The requirements for efficient suspension burning are entirely different, however, and considerable caution is recommended when endeavoring to combine the two concepts.

ENTRAINMENT REDUCED WITH FUEL CHUTE

Ideally, all the fuel should be delivered to the top of the fuel pile at a uniform rate and in such manner that the fine particles do not become entrained in the rising stream of hot gases. This can be accomplished quite easily with fuels of average consistency by the use of an inclined metal chute leading from the end of the conveyor to a point near the center of the burner and discharging not very far above the ultimate height of the fuel pile. The purpose of the chute is, of course, to shorten the distance through which the material must fall and to restrict the fall to the center of the burner where the velocity of the rotating gases is at a minimum.

If the chute is semi-circular in cross section, it also tends to concentrate the material into a condensed stream as contrasted to a fan shaped stream. The chute should have an open top so that it does not become a chimney, and to reduce the danger of its becoming plugged. Some experimentation may be necessary to determine the best cross-sectional shape and angle of slope for the particular type of fuel at hand. The slope may be made adjustable by hanging the lower end of the chute from the opposite site of the burner with cables.

AIR CONVEYED FINES POSE PROBLEM

The discharge of materials from the tailpipe of a collector is sometimes handled in a similar manner, that is, by extending the tailpipe so that it discharges to the center of the pile. However, problems often develop from material igniting inside the tailpipe and the fire then traveling upward into the cyclone itself. Plugging in the cyclone or the tailpipe can have disastrous results. The possibility of plugging can be reduced by carefully adjusting the cyclone to produce the correct downward flow of air through the tailpipe, but too much air defeats the intent by scattering the particles.

A preferable method is to install the cyclone above the conveyor leading to the burner, with its tailpipe discharging its materials into the conveyor through a surge bin. A small water spray is sometimes used to agglomerate the fine materials with the other refuse.

The practice of discharging fine materials directly into the burner from the air conveying pipe without benefit of an intermediary cyclone should be avoided at all costs because the material is introduced in association with a considerable volume of cold outside air from which it must become separated before it can ignite. If the air blast is directed toward the fuel pile, it will cool everything in the target area below ignition temperature; and if it is discharged above the fuel pile, the suspended particles have little chance of being consumed before they reach the top of the burner, if they ignite at all.

The only approach which appears to offer a possibility of success is to introduce the conveying air and its materials tangentially near the base of the burner as an integral part of the overfire air system. This method should not be used, however, unless the volume of air-conveyed material is nominal and the particles are sufficiently small in size to remain suspended until they are burned in association with the producer gas. Coarse particles which tend to fall out rather than remain suspended in the rotating air stream will soon form a windrow of half burned material if they are introduced in appreciable quantities. At best the method requires careful adjustment of the overfire air volume and the air conveying system should not be placed in operation until the temperature in the burner can be maintained above that necessary to ignite and burn the suspended particles completely before they reach the top of the burner.

Sander dust is often inroduced to the burner by a similar method, sometimes through a ring of gas jets to provide ignition. Because sander dust is made up of very fine particles, it behaves very much like a combustible gas. The following principles appear to apply:

(a) The air to fuel ratio is quite critical and must be adjustable. The conveying air volume is usually too great and an intermediary cyclone and a lower volume relay blower must be used.

(b) The fuel must be metered into the relay blower airstream at a continuous, uniform rate, as by means of a hopper and small screw conveyor.

(c) Satisfactory results are more likely if sander dust combustion is merely supplemental to the combustion of general residues in the fuel pile. In other words, the burner should receive enough general residue for efficient combustion without the sander dust to assure that ignition temperatures can be maintained for sufficient time to complete combustion of the suspended carbon.

OPEN FUEL PILE IS ITS OWN CHIMNEY

At the opposite extreme is a burner which receives only long, coarse residues. These materials tend to form a fuel pile resembling a loosely arranged pile of jackstraws. The stack creates its own chimney effect, with the individual pieces burning much as a group of torches. Gas combustion occurs within and above the stack and the rapidly rising thermal current created in the center of the burner dom-

inates the flow pattern. The advantages of circumferential flow are completely lost and the burning gases and particles take the shortest path to the top of the burner.

The problem is compounded if fine materials are introduced in association with the coarse, because they are discharged from the conveyor into the rising column of hot gases which then convey them by the shortest possible route out of the combustion zone and out of the burner.

The only apparent solution to this problem is to reduce the size of the pieces so that they will form a more compact fuel pile, and so that they can be delivered to the fuel pile in a chute.

CASUAL CUSTOMER CONDEMNED

Some mills are faced with the problem of having a customer for some of their residues who calls for them intermittently, with the result that the burner also receives materials intermittently. Even though the burner and its underfire and overfire air systems may be sized for the **average** quantity of material the burner receives over the period of a day's operation, the net result is a "feast and famine" routine. The fuel pile then goes through recurring cycles of burndown followed by smothering with a pattern of smoke discharge to match.

The solution to this problem is of course to even out the material flow rate to some sort of an average value. One suggestion is to provide a storage bin to which the percentage of the residues to be sold can be continuously diverted; another is to divert all the material to a storage facility for the number of days per week that will satisfy the customer's needs, and then operate the burner the remainder of the week at the full rate of residue production. The only truly successful solution is of course to find a customer for the remaining residues and sell the burner.

6. MAINTENANCE AND OPERATION . INSTRUMENTS

Even the best burner will be a smoke or fallout generator if it is not conscientiously maintained and operated. Except for the periodic repair work necessary to keep the burner and its associated parts in top structural and mechanical condition, maintenance is essentially a matter of ash and clinker removal.

PLUGGED OUTLETS SELF-ESCALATING

If the plant is on a one-shift schedule, ash and clinker removal can usually be taken care of with clinker removal once a day and ash removal once a week. The clinkers must be frequently removed from the underfire air outlets so that air flow will not be restricted by their accumulation. They can be tossed to one side for weekly removal from the burner along with the ashes. The underfire system should be left on overnight as necessary to burn all of the material by morning so that access for clinker removal is possible.

When a plant is in production for more than one shift, or if the fuel includes very much thick material, the fuel pile may not burn down sufficiently to allow daily clinker removal. In such cases, a type of outlet that will not readily bridge over is needed. Sometimes removal is possible by the use of a long-handled pair of tongs and by wearing asbestos padded boots. The important thing is to keep all of the outlets open.

If only some of the outlets are open, channeling will develop and the fuel pile will grow larger. The situation can develop into a vicious cycle and get out of hand. Fewer effective outlets mean less efficient combustion and a longer burning fuel pile, which in turn reduces the possibility of daily access to the remaining outlets to keep them open. Ultimately, the effectiveness of the underfire air system can be reduced to the point that the fuel pile will cease to function as a gas producer and grow so large as to endanger the burner shell.

GOOD DESIGN PRECLUDES LEAKY DOORS

Many burners have a built-in maintenance problem that is a by-product of ash and clinker removal. This has to do with the access doors, which too often become warped or damaged and consequently admit volumes of uncontrolled overfire air. Large doors are especially troublesome as they are more prone to warp from intense radiant heat. An insulation liner or metal heat shield on the doors is quite effective in eliminating warping. Double doors seldom meet at their edges, so an overlapping metal plate should be used to close the gap between them.

The most common source of door leakage is at the sills, and this is where leakage is most undesirable because the resulting air jet is directed along the floor of the burner directly at the fuel pile. The effect is to short-circuit the cricumferential flow pattern and enhance the natural tendency of the gases to rise in a column up the center of the burner. Sill leakage can be minimized by providing a concrete apron under the door. Door clearance over the apron should be no more than ½ inch, or a door stop or some type of closure such as a hinged plate should be used to close the gap.

BIG FIRE SHORTENS SMOKY START-UP

Correct operation starts on Monday morning (after the clinkers and ashes have been removed) with the kindling of a new fire. This should be a whopping bonfire, with easily ignited dry kindling overlain with longer and heavier coarse material arranged in an open pattern. The underfire air system should be turned on with damper set for low flow, and the overfire ports should be full open. The fire should be burning briskly by the time the first refuse arrives from the mill.

The mill refuse will soon cover the bonfire and until it dries sufficiently for the distillation process to generate gases that are rich enough to ignite, great volumes of smoke will pour from the top of the burner. At this stage the underfire air volume should be increased to near maximum. The overfire air inlets should remain wide open, because stack effect will still be minimal due to lack of burner temperature.

As soon as the volatile gases ignite and burn steadily, the burner temperature will begin its rise. From this point on, the overfire volume should be periodically readjusted as necessary to match the increasing gas generation rate with the best proportion of overfire air. Too much overfire air cools and dilutes the gases so that they will not ignite and appear as white smoke. Too little deprives the gases of the oxygen they need to burn completely as evidenced by darker smoke. With experience the initial period of heavy smoke emission can usually be trimmed to less than one half hour.

UNDERFIRE AIR CONTROLS PILE SIZE

By the time the temperature inside the burner has reached a level that assures complete combustion of the gases and suspended carbon particles, the overfire ports should be at approximately their normal operating position. The underfire air volume may now need to be reduced somewhat to allow the fuel pile to grow until the outermost outlets are covered by at least 3 feet of fuel, at which time the air volume should be increased to the setting that will maintain the pile at this size. If the fuel feed rate varies, the underfire air volume will require periodic readjustment to compensate. The size of the fuel pile should dictate the underfire air damper position.

A common error is to operate with too much underfire air. This reduces the size of the fuel pile because the combustion rate is increased. The temporary increase in burner temperature and more vigorous combustion can easily be interpreted as signifying a better underfire air setting. It may appear better because the excess of underfire oxygen causes gas combustion within the pile, as evidenced by excessive channelling or "blowholes." The combustion rate cannot exceed the rate of fuel introduction for long, however, or the end result will be rapid surface combustion of a small pile in lieu of controlled gas generation in a large pile.

Frequent visual inspection of the fuel pile provides much of the information needed for the correct setting for the underfire air damper, and the most useful device

for this purpose is simply a horizontal slot in the burner shell at eye level. A good size is 8" x 1½", and two should be provided, on opposite sides of the burner.

The information needed to determine the best setting for the overfire air inlets is a bit more elusive, however, because it has to do with temperature.

TEMPERATURE INDEX TO BEST ADJUSTMENT

Test data developed by Dr. R. W. Boubel of Oregon State University from studies of a number of waste burners has shown that there is a definite relationship between smoke discharge and the temperature of the gases leaving the burner. This data is presented in detail in O.S.U. Engineering Experiment Station Circular No. 34. In more recent studies, Dr. Boubel has developed similar data which indicates the relationship between burner exit temperature and the discharge of particles.

As a guide to correct operation, the data may be roughly summarized as indicating that least smoke is observed at exit temperatures of over 650 degrees, and least particle discharge at temperatures from 500 to 600 degrees. Simply stated, higher temperatures decrease smoke but increase fallout. Results vary between individual burners and fuels, but the best overall results are usually obtained at some point between 500 and 900 degrees exit temperature.

From this it is apparent that correct adjustment depends upon knowledge of the exit temperature. Smoke discharge can be evaluated somewhat by observation, but the discharge of particles that will descend to create nuisance conditions in the surrounding area sometimes cannot be seen. Only through experience gained by experimentation with the adjustments to an individual burner can the best operating point for that burner be found, and this experimentation can only yield correct answers when the effect of a change in adjustment on exit temperature can be observed.

PYROMETER MEASURES HIGH TEMPERATURES

The most practical instrument for measuring exit temperatures is a pyrometer. This is a commonly used device that utilizes a simple principle: that when the ends of two wires made of different metals are twisted together and the juncture heated, measurable electrical voltage will be generated. The higher the temperature, the greater the voltage.

If we connect the free ends of the two wires to a gauge that measure the amount of voltage, we will have an indication of the temperature that generated the voltage. The gauge, called a millivoltmeter, when calibrated in degrees temperature instead of millivolts becomes a pyrometer.

The juncture of the two dissimilar metals is referred to as a thermocouple. A number of different metal alloys have been developed for thermocouples, and there is a best combination for any specific purpose. The thermocouple type usually recommended for measuring burner exit temperatures is designated as "chromel-alumel, type K." "Iron-constantan" type is sometimes used, but it deteriorates in a hot flue gas environment. The thermocouple is usually mounted at the end of a stainless steel extension tube so that it senses the temperature about 6 feet inside the top of the burner shell.

RECORDING PYROMETER BEST CHOICE

What we have described is an "indicating pyrometer." With such an instrument mounted at a convenient location near the burner, it is possible to determine at a glance what the exit temperature may be at any given moment. The pyrometer will yield much more useful information, however, if it is of the recording type. A recorder tells not only what the temperature is, but what it has been, and whether it is rising or falling.

There are two principal types of recording pyrometer commercially available, the recording potentiometer and the miniature recording pyrometer. Because the voltage generated by the thermocouple is quite small it can't provide enough power to drag a pen across a chart, so until recent years a recorder of necessity included an electrical amplifier, was called a recording potentiometer and was quite expensive. More recently, however, the miniature recorder has become available at considerably less cost.

The miniature recorder uses a clock type motor to move a small strip chart beneath the indicating hand of the millivoltmeter. The hand has a small stylus attached to its underneath side. At intervals of about 2 seconds, a clapper presses the stylus against the chart, which is pressure sensitive, and imprints a small dot which indicates the temperature at that moment. Over a period of time, the series of closely spaced dots appears as a continuous line.

Miniature recording pyrometers require an external source of electrical power to run the chart motor and actuate the clapper. A temperature range of 0 to 1500 degrees is recommended to avoid over-stressing the meter by an inordinately high temperature. These instruments are not very rugged and they should be mounted where they will be well protected from weather, vibration and shock.

The thermocouple lead wire, which runs from the thermocouple to the pyrometer, should be carefully routed so that it is not exposed to possible physical damage, and it should be supported on outriggers so that it is not in contact with the burner shell. It should not be pulled taut, as its length will vary with temperature.

When experience has shown the best damper positions as evidenced by fuel pile size and exit temperature, a periodic recheck and readjustment is all that is needed to obtain reasonably consistent results, **if the delivery rate and characteristics of the fuel are consistent.** If they are not, more frequent readjustment is necessary.

Minor variations in delivery rate are not significant if the average over a period of any 2 or 3 hours is consistent. Also, coarse materials tend to compensate for variations by a "flywheel" effect resulting from their slow rate of carbonization. Thin materials, however, respond quite rapidly to changes and require more frequent damper readjustment.

Variations in the species of wood being processed have a pronounced effect on adjustment, primarily due to variations in moisture content. The amount of moisture also varies with the time of year and is greater for pond logs than dry-decked logs, especially if the refuse is predominantly bark. During the rainy season, refuse as received at the burner from an exposed conveyor may carry additional water on its surfaces, adding further to the moisture load.

Additional moisture means that additional heat is expended in its' evaporation, and that the additional water vaper cools and dilutes the volatile gases. The effect on operation is that higher temperatures are more difficult to attain. The best procedure to follow when confronted with this difficulty is to increase the underfire and decrease the overfire air. For reasons that are a bit elusive, the degree of reduction in overfire air that gives best results with very high moisture loads sometimes borders on the unbelievable.

Conversely, the refuse produced from dry-decked logs in hot dry weather can be so low in moisture content as to create an overheating problem. The operating procedure is then to adjust for maximum overfire air to take advantage of its cooling effect. In an emergency situation, the doors may need to be opened to admit further cooling air. The underfire air should **not** be reduced because the fuel pile would then increase in size, confining the already inordinately high temperature flames into a narrow space close to the burner shell.